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(54) **ADAPTABLE DATAPATH FOR A DIGITAL PROCESSING SYSTEM**

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(58) **Field of Classification Search** ..... None  
See application file for complete search history.

(56) **References Cited**

**U.S. PATENT DOCUMENTS**

3,409,175	A	11/1968	Byrne
3,666,143	A	5/1972	Weston
3,938,639	A	2/1976	Birrell
3,949,903	A	4/1976	Benasutti et al.

3,960,298	A	6/1976	Birrell
3,967,062	A	6/1976	Dobias
3,991,911	A	11/1976	Shannon et al.
3,995,441	A	12/1976	McMillin
4,076,145	A	2/1978	Zygiel
4,143,793	A	3/1979	McMillin et al.
4,172,669	A	10/1979	Edelbach
4,174,872	A	11/1979	Fessler
4,181,242	A	1/1980	Zygiel et al.
RE30,301	E	6/1980	Zygiel
4,218,014	A	8/1980	Tracy
4,222,972	A	9/1980	Caldwell
4,237,536	A	12/1980	Enelow et al.

(Continued)

**FOREIGN PATENT DOCUMENTS**

DE	100 18 374	A1	10/2001
EP	0 301 169	A1	2/1989

(Continued)

**OTHER PUBLICATIONS**

Abnous et al., "Ultra-Low-Power Domain-Specific Multimedia Processors," VLSI Signal Processing, IX, 1998, IEEE Workshop in San Francisco, CA, USA, Oct. 30-Nov. 1, 1998, pp. 461-470 (Oct. 30, 1998).

(Continued)

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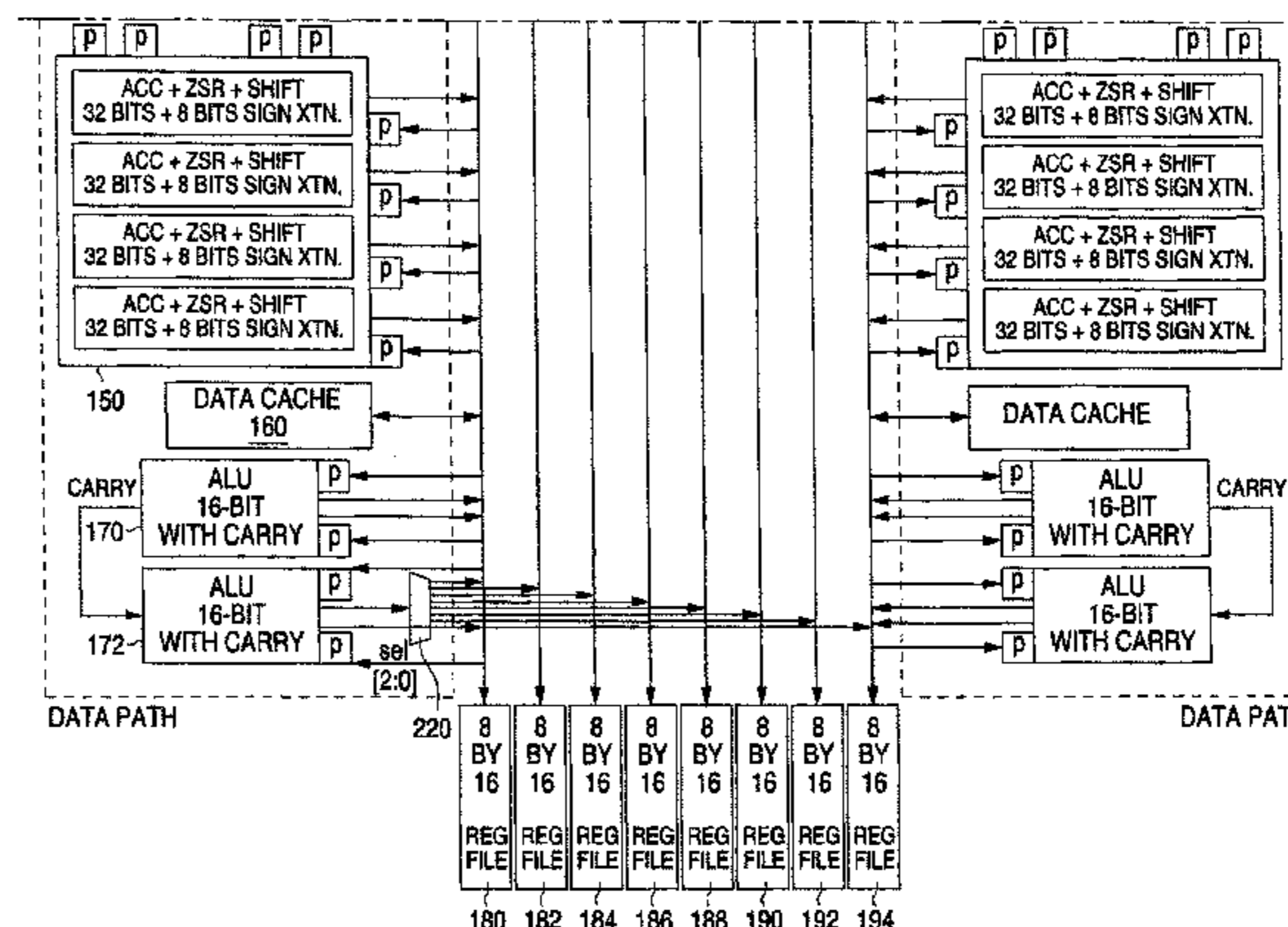
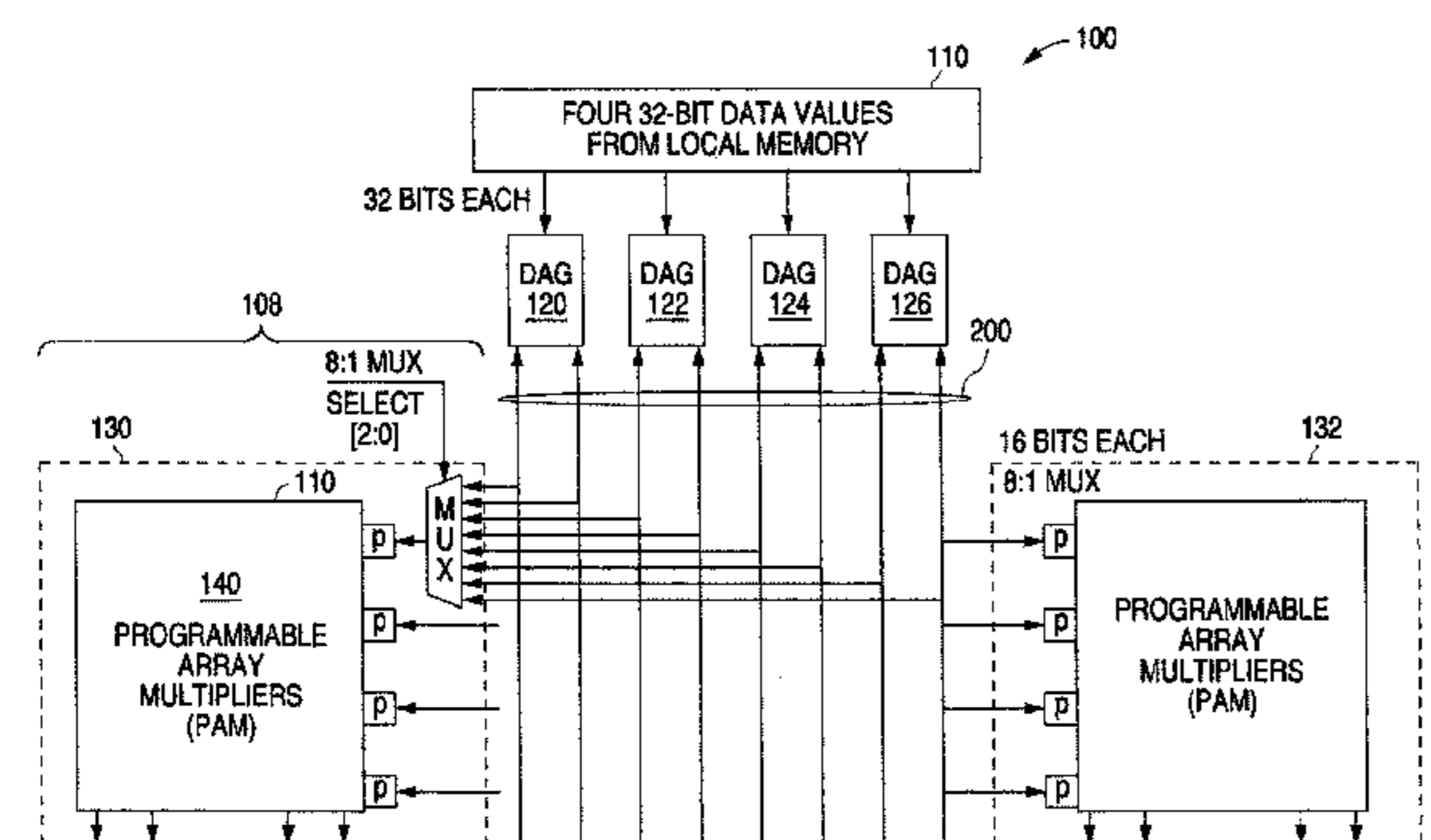
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(57) **ABSTRACT**

The present invention includes an adaptable high-performance node (RXN) with several features that enable it to provide high performance along with adaptability. A preferred embodiment of the RXN includes a run-time configurable data path and control path. The RXN supports multi-precision arithmetic including 8, 16, 24, and 32 bit codes. Data flow can be reconfigured to minimize register accesses for different operations. For example, multiply-accumulate operations can be performed with minimal, or no, register stores by reconfiguration of the data path. Predetermined kernels can be configured during a setup phase so that the RXN can efficiently execute, e.g., Discrete Cosine Transform (DCT), Fast-Fourier Transform (FFT) and other operations. Other features are provided.

**33 Claims, 3 Drawing Sheets**



U.S. PATENT DOCUMENTS							
4,252,253	A	2/1981	Shannon	5,368,198	A	11/1994	Goulet
4,302,775	A	11/1981	Widergren et al.	5,379,343	A	1/1995	Grube et al.
4,333,587	A	6/1982	Fessler et al.	5,381,546	A	1/1995	Servi et al.
4,354,613	A	10/1982	Desai et al.	5,381,550	A	1/1995	Jourdenais et al.
4,377,246	A	3/1983	McMillin et al.	5,388,212	A	2/1995	Grube et al.
4,393,468	A	7/1983	New	5,392,960	A	2/1995	Kendt et al.
4,413,752	A	11/1983	McMillin et al.	5,437,395	A	8/1995	Bull et al.
4,458,584	A	7/1984	Annese et al.	5,450,557	A	9/1995	Kopp et al.
4,466,342	A	8/1984	Basile et al.	5,454,406	A	10/1995	Rejret et al.
4,475,448	A	10/1984	Shoaf et al.	5,465,368	A	11/1995	Davidson et al.
4,509,690	A	4/1985	Austin et al.	5,479,055	A	12/1995	Eccles
4,520,950	A	6/1985	Jeans	5,490,165	A	2/1996	Blakeney, II et al.
4,549,675	A	10/1985	Austin	5,491,823	A	2/1996	Ruttenberg
4,553,573	A	11/1985	McGarrah	5,507,009	A	4/1996	Grube et al.
4,560,089	A	12/1985	McMillin et al.	5,515,519	A	5/1996	Yoshioka et al.
4,577,782	A	3/1986	Fessler	5,517,600	A	5/1996	Shimokawa
4,578,799	A	3/1986	Scholl et al.	5,519,694	A	5/1996	Brewer et al.
RE32,179	E	6/1986	Sedam et al.	5,522,070	A	5/1996	Sumimoto
4,633,386	A	12/1986	Terepin et al.	5,530,964	A	6/1996	Alpert et al.
4,658,988	A	4/1987	Hassell	5,534,796	A	7/1996	Edwards
4,694,416	A	9/1987	Wheeler et al.	5,542,265	A	8/1996	Rutland
4,711,374	A	12/1987	Gaunt et al.	5,553,755	A	9/1996	Bonewald et al.
4,713,755	A	12/1987	Worley, Jr. et al.	5,555,417	A	9/1996	Odnert et al.
4,719,056	A	1/1988	Scott	5,560,028	A	9/1996	Sachs et al.
4,726,494	A	2/1988	Scott	5,560,038	A	9/1996	Haddock
4,747,516	A	5/1988	Baker	5,570,587	A	11/1996	Kim
4,748,585	A	5/1988	Chiarulli et al.	5,572,572	A	11/1996	Kawan et al.
4,760,525	A	7/1988	Webb	5,590,353	A	12/1996	Sakakibara et al.
4,760,544	A	7/1988	Lamb	5,594,657	A	1/1997	Cantone et al.
4,765,513	A	8/1988	McMillin et al.	5,600,810	A	2/1997	Ohkami
4,766,548	A	8/1988	Cedrone et al.	5,600,844	A	2/1997	Shaw et al.
4,781,309	A	11/1988	Vogel	5,602,833	A	2/1997	Zehavi
4,800,492	A	1/1989	Johnson et al.	5,603,043	A	2/1997	Taylor et al.
4,811,214	A	3/1989	Nosenchuck et al.	5,607,083	A	3/1997	Vogel et al.
4,824,075	A	4/1989	Holzboog	5,608,643	A	3/1997	Wichter et al.
4,827,426	A	5/1989	Patton et al.	5,611,867	A	3/1997	Cooper et al.
4,850,269	A	7/1989	Hancock et al.	5,623,545	A	4/1997	Childs et al.
4,856,684	A	8/1989	Gerstung	5,625,669	A	4/1997	McGregor et al.
4,901,887	A	2/1990	Burton	5,626,407	A	5/1997	Westcott
4,921,315	A	5/1990	Metcalfe et al.	5,630,206	A	5/1997	Urban et al.
4,930,666	A	6/1990	Rudick	5,635,940	A	6/1997	Hickman et al.
4,932,564	A	6/1990	Austin et al.	5,646,544	A	7/1997	Iadanza
4,936,488	A	6/1990	Austin	5,646,545	A	7/1997	Trimberger et al.
4,937,019	A	6/1990	Scott	5,647,512	A	7/1997	Assis Mascarenhas de Oliveira et al.
4,960,261	A	10/1990	Scott et al.	5,667,110	A	9/1997	McCann et al.
4,961,533	A	10/1990	Teller et al.	5,684,793	A	11/1997	Kiema et al.
4,967,340	A	10/1990	Dawes	5,684,980	A	11/1997	Casselman
4,974,643	A	12/1990	Bennett et al.	5,687,236	A	11/1997	Moskowitz et al.
4,982,876	A	1/1991	Scott	5,694,613	A	12/1997	Suzuki
4,993,604	A	2/1991	Gaunt et al.	5,694,794	A	12/1997	Jerg et al.
5,007,560	A	4/1991	Sassak	5,699,328	A	12/1997	Ishizaki et al.
5,021,947	A	6/1991	Campbell et al.	5,701,482	A	12/1997	Harrison et al.
5,040,106	A	8/1991	Maag	5,704,053	A	12/1997	Santhanam
5,044,171	A	9/1991	Farkas	5,706,191	A	1/1998	Bassett et al.
5,090,015	A	2/1992	Dabbish et al.	5,706,976	A	1/1998	Purkey
5,129,549	A	7/1992	Austin	5,712,996	A	1/1998	Schepers
5,139,708	A	8/1992	Scott	5,720,002	A	2/1998	Wang
5,156,301	A	10/1992	Hassell et al.	5,721,693	A	2/1998	Song
5,156,871	A	10/1992	Goulet et al.	5,721,854	A	2/1998	Ebcioglu et al.
5,165,575	A	11/1992	Scott	5,732,563	A	3/1998	Bethuy et al.
5,190,083	A	3/1993	Gupta et al.	5,734,808	A	3/1998	Takeda
5,190,189	A	3/1993	Zimmer et al.	5,737,631	A	4/1998	Trimberger
5,193,151	A	3/1993	Jain	5,742,180	A	4/1998	DeHon et al.
5,193,718	A	3/1993	Hassell et al.	5,742,821	A	4/1998	Prasanna
5,202,993	A	4/1993	Tarsy et al.	5,745,366	A	4/1998	Higham et al.
5,203,474	A	4/1993	Haynes	RE35,780	E	5/1998	Hassell et al.
5,240,144	A	8/1993	Feldman	5,751,295	A	5/1998	Becklund et al.
5,261,099	A	11/1993	Bigo et al.	5,754,227	A	5/1998	Fukuoka
5,263,509	A	11/1993	Cherry et al.	5,758,261	A	5/1998	Wiedeman
5,269,442	A	12/1993	Vogel	5,768,561	A	6/1998	Wise
5,280,711	A	1/1994	Motta et al.	5,778,439	A	7/1998	Trimberger et al.
5,297,400	A	3/1994	Benton et al.	5,784,636	A	7/1998	Rupp
5,301,100	A	4/1994	Wagner	5,787,237	A	7/1998	Reilly
5,303,846	A	4/1994	Shannon	5,790,817	A	8/1998	Asghar et al.
5,335,276	A	8/1994	Thompson et al.	5,791,517	A	8/1998	Avital
5,339,428	A	8/1994	Burmeister et al.	5,791,523	A	8/1998	Oh
5,343,716	A	9/1994	Swanson et al.	5,794,062	A	8/1998	Baxter
5,361,362	A	11/1994	Benkeser et al.	5,794,067	A	8/1998	Kadowaki

5,802,055	A	9/1998	Krein et al.	6,091,765	A	7/2000	Pietzold, III et al.
5,818,603	A	10/1998	Motoyama	6,094,065	A	7/2000	Tavana et al.
5,822,308	A	10/1998	Weigand et al.	6,094,726	A	7/2000	Gonion et al.
5,822,313	A	10/1998	Malek et al.	6,111,893	A	8/2000	Volftsun et al.
5,822,360	A	10/1998	Lee et al.	6,111,935	A	8/2000	Hughes-Hartogs
5,828,858	A	10/1998	Athanas et al.	6,115,751	A	9/2000	Tam et al.
5,829,085	A	11/1998	Jerg et al.	6,120,551	A	9/2000	Law et al.
5,835,753	A	11/1998	Witt	6,122,670	A	9/2000	Bennett et al.
5,838,165	A	11/1998	Chatter	6,138,693	A	10/2000	Matz
5,845,815	A	12/1998	Vogel	6,141,283	A	10/2000	Bogin et al.
5,860,021	A	1/1999	Klingman	6,150,838	A	11/2000	Wittig et al.
5,862,961	A	1/1999	Motta et al.	6,154,494	A	11/2000	Sugahara et al.
5,870,427	A	2/1999	Tiedemann, Jr. et al.	6,157,997	A	12/2000	Oowaki et al.
5,873,045	A	2/1999	Lee et al.	6,175,854	B1	1/2001	Bretscher
5,881,106	A	3/1999	Cartier	6,175,892	B1	1/2001	Sazzad et al.
5,884,284	A	3/1999	Peters et al.	6,181,981	B1	1/2001	Varga et al.
5,886,537	A	3/1999	Macias et al.	6,185,418	B1	2/2001	MacLellan et al.
5,887,174	A	3/1999	Simons et al.	6,192,070	B1	2/2001	Poon et al.
5,889,816	A	3/1999	Agrawal et al.	6,192,255	B1	2/2001	Lewis et al.
5,890,014	A	3/1999	Long	6,192,388	B1	2/2001	Cajolet
5,892,900	A	4/1999	Ginter et al.	6,195,788	B1	2/2001	Leaver et al.
5,892,961	A	4/1999	Trimberger	6,198,924	B1	3/2001	Ishii et al.
5,894,473	A	4/1999	Dent	6,199,181	B1	3/2001	Rechef et al.
5,901,884	A	5/1999	Goulet et al.	6,202,130	B1	3/2001	Scales, III et al.
5,903,886	A	5/1999	Heimlich et al.	6,219,697	B1	4/2001	Lawande et al.
5,907,285	A	5/1999	Toms et al.	6,219,756	B1	4/2001	Kasamizugami
5,907,580	A	5/1999	Cummings	6,219,780	B1	4/2001	Lipasti
5,910,733	A	6/1999	Bertolet et al.	6,223,222	B1	4/2001	Fijolek et al.
5,912,572	A	6/1999	Graf, III	6,226,387	B1	5/2001	Tewfik et al.
5,913,172	A	6/1999	McCabe et al.	6,230,307	B1	5/2001	Davis et al.
5,917,852	A	6/1999	Butterfield et al.	6,237,029	B1	5/2001	Master et al.
5,920,801	A	7/1999	Thomas et al.	6,246,883	B1	6/2001	Lee
5,931,918	A	8/1999	Row et al.	6,247,125	B1	6/2001	Noel-Baron et al.
5,933,642	A	8/1999	Greenbaum et al.	6,249,251	B1	6/2001	Chang et al.
5,933,855	A	8/1999	Rubinstein	6,258,725	B1	7/2001	Lee et al.
5,940,438	A	8/1999	Poon et al.	6,263,057	B1	7/2001	Silverman
5,949,415	A	9/1999	Lin et al.	6,266,760	B1	7/2001	DeHon et al.
5,950,011	A	9/1999	Albrecht et al.	6,272,579	B1	8/2001	Lentz et al.
5,950,131	A	9/1999	Vilmur	6,281,703	B1	8/2001	Furuta et al.
5,951,674	A	9/1999	Moreno	6,282,627	B1	8/2001	Wong et al.
5,953,322	A	9/1999	Kimball	6,289,375	B1	9/2001	Knight et al.
5,956,518	A	9/1999	DeHon et al.	6,289,434	B1	9/2001	Roy
5,956,967	A	9/1999	Kim	6,289,488	B1	9/2001	Dave et al.
5,959,811	A	9/1999	Richardson	6,292,822	B1	9/2001	Hardwick
5,959,881	A	9/1999	Trimberger et al.	6,292,827	B1	9/2001	Raz
5,963,048	A	10/1999	Harrison et al.	6,292,830	B1	9/2001	Taylor et al.
5,966,534	A	10/1999	Cooke et al.	6,301,653	B1	10/2001	Mohamed et al.
5,970,254	A	10/1999	Cooke et al.	6,305,014	B1	10/2001	Roediger et al.
5,987,105	A	11/1999	Jenkins et al.	6,311,149	B1	10/2001	Ryan et al.
5,987,611	A	11/1999	Freund	6,321,985	B1	11/2001	Kolls
5,991,302	A	11/1999	Berl et al.	6,346,824	B1	2/2002	New
5,991,308	A	11/1999	Fuhrmann et al.	6,347,346	B1	2/2002	Taylor
5,993,739	A	11/1999	Lyon	6,349,394	B1	2/2002	Brock et al.
5,999,734	A	12/1999	Willis et al.	6,353,841	B1	3/2002	Marshall et al.
6,005,943	A	12/1999	Cohen et al.	6,356,994	B1	3/2002	Barry et al.
6,006,249	A	12/1999	Leong	6,359,248	B1	3/2002	Mardi
6,016,395	A	1/2000	Mohamed	6,360,256	B1	3/2002	Lim
6,021,186	A	2/2000	Suzuki et al.	6,360,259	B1	3/2002	Bradley
6,021,492	A	2/2000	May	6,360,263	B1	3/2002	Kurtzberg et al.
6,023,742	A	2/2000	Ebeling et al.	6,363,411	B1	3/2002	Dugan et al.
6,023,755	A	2/2000	Casselmann	6,366,999	B1	4/2002	Drabenstott et al.
6,028,610	A	2/2000	Deering	6,377,983	B1	4/2002	Cohen et al.
6,036,166	A	3/2000	Olson	6,378,072	B1	4/2002	Collins et al.
6,039,219	A	3/2000	Bach et al.	6,381,735	B1	4/2002	Hunt
6,041,322	A	3/2000	Meng et al.	6,385,751	B1	5/2002	Wolf
6,041,970	A	3/2000	Vogel	6,405,214	B1	6/2002	Meade, II
6,046,603	A	4/2000	New	6,408,039	B1	6/2002	Ito
6,047,115	A	4/2000	Mohan et al.	6,410,941	B1	6/2002	Taylor et al.
6,052,600	A	4/2000	Fette et al.	6,411,612	B1	6/2002	Halford et al.
6,055,314	A	4/2000	Spies et al.	6,421,372	B1	7/2002	Bierly et al.
6,056,194	A	5/2000	Kolls	6,421,809	B1	7/2002	Wuytack et al.
6,059,840	A	5/2000	Click, Jr.	6,430,624	B1	8/2002	Jamtgaard et al.
6,061,580	A	5/2000	Altschul et al.	6,433,578	B1	8/2002	Wasson
6,073,132	A	6/2000	Gehman	6,434,590	B1	8/2002	Blelloch et al.
6,076,174	A	6/2000	Freund	6,438,737	B1	8/2002	Morelli et al.
6,078,736	A	6/2000	Guccione	6,456,996	B1	9/2002	Crawford, Jr. et al.
6,085,740	A	7/2000	Ivri et al.	6,459,883	B2	10/2002	Subramanian et al.
6,088,043	A	7/2000	Kelleher et al.	6,473,609	B1	10/2002	Schwartz et al.
6,091,263	A	7/2000	New et al.	6,507,947	B1	1/2003	Schreiber et al.



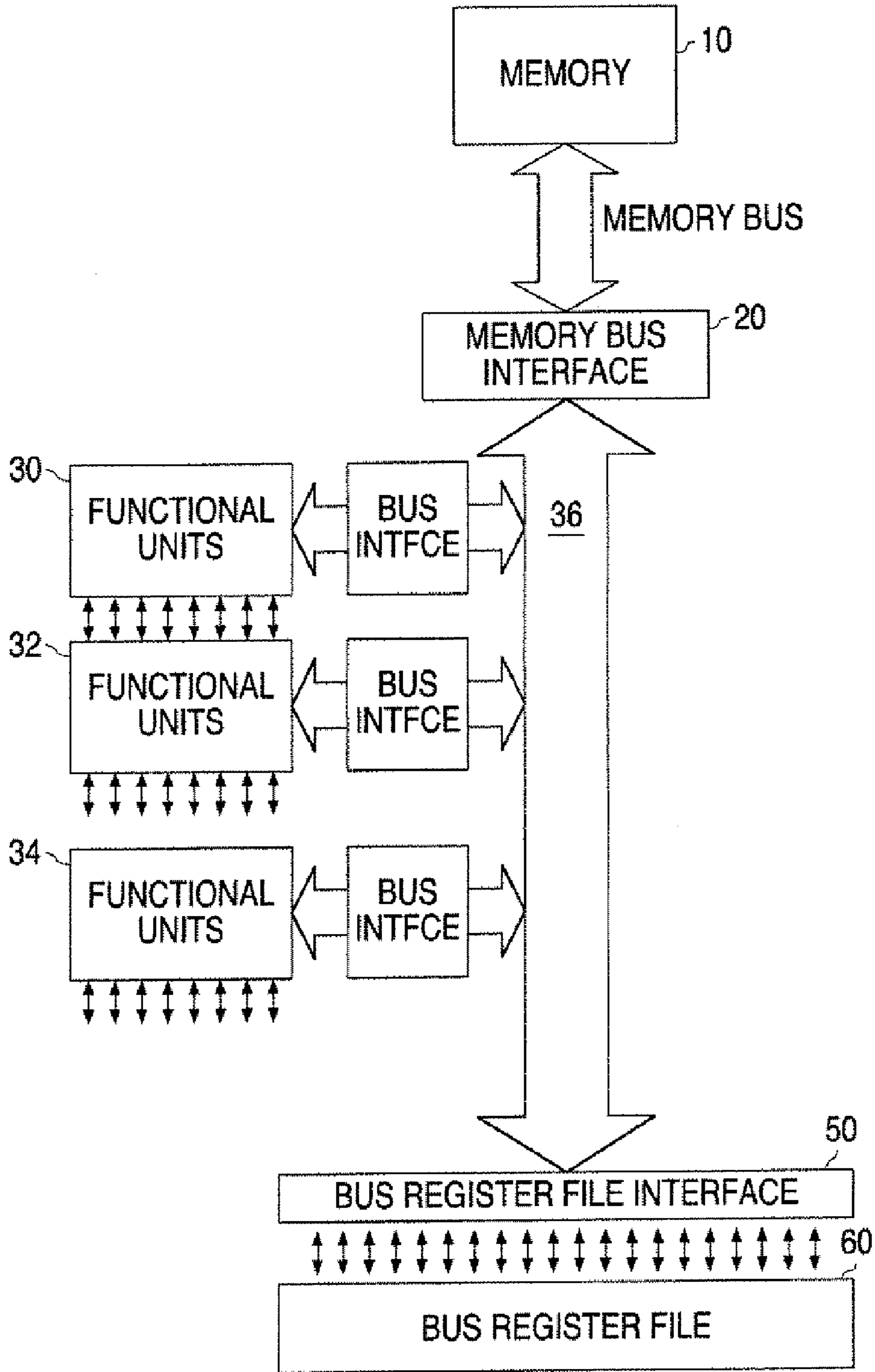
JP	63-147258	6/1988
JP	4-51546	2/1992
JP	7-064789	3/1995
JP	7066718	3/1995
JP	10233676	9/1998
JP	10254696	9/1998
JP	11296345	10/1999
JP	2000315731	11/2000
JP	2001-053703	2/2001
WO	WO 89/05029 A1	6/1989
WO	WO 89/11443 A2	11/1989
WO	WO 91/00238 A1	1/1991
WO	WO 93/13603 A1	7/1993
WO	WO 95/11855 A1	5/1995
WO	WO 96/33558 A1	10/1996
WO	WO 98/32071 A3	7/1998
WO	WO 99/03776 A1	1/1999
WO	WO 99/21094 A2	4/1999
WO	WO 99/26860 A1	6/1999
WO	WO 99/65818 A1	12/1999
WO	WO 00/19311 A1	4/2000
WO	WO 00/65855 A1	11/2000
WO	WO 00/69073 A1	11/2000
WO	WO 01/11281 A1	2/2001
WO	WO 01/22235 A1	3/2001
WO	WO 01/76129 A2	10/2001
WO	WO 02/12978 A2	2/2002

## OTHER PUBLICATIONS

- Aggarwal et al., "Efficient Huffman Decoding," International Conference on Image Processing IEEE 1:936-939 (Sep. 10-13, 2000).
- Allan et al., "Software Pipelining," ACM Computing Surveys, 27(3):1-78 (Sep. 1995).
- Alsolaim et al., "Architecture and Application of a Dynamically Reconfigurable Hardware Array for Future Mobile Communication Systems," Field Programmable Custom Computing Machines, 2000 IEEE Symposium, Napa Valley, Los Alamitos, CA. IEEE Comput. Soc. pp. 205-214 (Apr. 17-19, 2000).
- Ashenden et al., "The VHDL Cookbook," Dept. Computer Science, University of Adelaide, South Australia. Downloaded from <http://tams-www.informatik.uni-hamburg.de/vhdl/doc/cookbook/VHDL-Cookbook.pdf> on Dec. 7, 2006 (Jul. 1990).
- Bacon et al., "Compiler Transformations for High-Performance Computing," ACM Computing Surveys 26(4):368-373 (Dec. 1994).
- Balasubramonian et al., "Reducing the Complexity of the Register File in Dynamic Superscalar Processors," Proceedings of the 34th Annual ACM/IEEE International Symposium on Microarchitecture, pp. 237-248 (Dec. 1, 2001).
- Banerjee et al., "A Matlab Compiler for Distributed, Heterogeneous, Reconfigurable Computing Systems," 2000 IEEE Symposium, pp. 39-48, (Apr. 17-19, 2000).
- Bapte et al., "Uniform Execution Environment for Dynamic Reconfiguration," Darpa Adaptive Computing Systems, [http://isis.vanderbilt.edu/publications/archive/babty\\_T\\_#\\_0\\_1999\\_Uniform\\_Ex.pdf](http://isis.vanderbilt.edu/publications/archive/babty_T_#_0_1999_Uniform_Ex.pdf), pp. 1-7 (1999).
- Baumgarte et al., "PACT XPP—A Self-Reconfigurable Data Processing Architecture," NN [www.pactcorp.com/sneu/download/ersa01.pdf](http://www.pactcorp.com/sneu/download/ersa01.pdf); retrieved on Nov. 25, 2005 (Jun. 25, 2001).
- Becker et al., "An Application-Tailored Dynamically Reconfigurable Hardware Architecture for Digital Baseband Processing," IEEE Conference Proceedings Article pp. 341-346 (Sep. 18, 2000).
- Becker et al., "Design and Implementation of a Coarse-Grained Dynamically Reconfigurable Hardware Architecture," VLSI 2001, Proceedings IEEE Computer Soc. Workshop, Piscataway, NJ, USA, pp. 41-46 (Apr. 19-20, 2001).
- Bevstar, BevStar Bottled Water Model Advertisement *Automatic Merchandiser* at [www.AMonline.com](http://www.AMonline.com) (2005).
- Bevstar, BevStar Point of Use Water Model Advertisement *Automatic Merchandiser* at [www.AMonline.com](http://www.AMonline.com) (2005).
- Bishop & Loucks, "A Heterogeneous Environment for Hardware/Software Cosimulation," Proceedings of the 30th Annual Simulation Symposium, pp. 14-22 (Apr. 7-9, 1997).
- Brakensiek et al., "Re-Configurable Multi-Standard Terminal for Heterogeneous Networks," Radio and Wireless Conference, Rawcon 2002 IEEE. pp. 27-30 (2002).
- Brown et al., "Quick PDA Data Exchange," PC Magazine pp. 1-3 (May 22, 2001).
- Buck et al., "Ptolemy: A Framework for Simulating and Prototyping Heterogeneous Systems," International Journal of Computer Simulation 4:155-182 (Apr. 1994).
- Burns et al., "A Dynamic Reconfiguration Run-Time System," Proceedings of the 5th Annual Symposium on Field-Programmable Custom Computing Machines, pp. 166-175 (Apr. 16, 1997).
- Business Wire, "Whirlpool Internet-Enabled Appliances to Use Bee-line Shopper Software Features," <http://www.whirlpoolcorp.com/news/releases/release.asp?rid=90> (Feb. 16, 2001).
- Buttazzo et al., "Optimal Deadline Assignment for Scheduling Soft Aperiodic Tasks in Hard Real-Time Environments," Engineering of Complex Computer Systems, Proceedings of the Third IEEE International Conference on Como, pp. 39-48 (Sep. 8, 1997).
- Callahan et al., "Adapting Software Pipelining for Reconfigurable Computing," in Proceedings of the International Conference on Compilers, Architecture and Synthesis for Embedded Systems p. 8, ACM (Cases '00, San Jose, CA) (Nov. 17-18, 2000).
- Chapman & Mehrotra, "OpenMP and HPF: Integrating Two Paradigms," Proceedings of the 4th International Euro-Par Conference (Euro-Par'98), Springer-Verlag Heidelberg, Lecture Notes in Computer Science 1470:650-658 (1998).
- Chen et al., "A Reconfigurable Multiprocessor IC for Rapid Prototyping of Algorithmic-Specific High-Speed DSP Data Paths," IEEE Journal of Solid-State Circuits, IEEE 35:74-75 (Feb. 1, 2001).
- Clarke, "Embedded Solutions Enters Development Pact with Marconi," EETimes Online (Jan. 26, 2000).
- Compton & Hauck, "Reconfigurable Computing: A Survey of Systems and Software," ACM Press, ACM Computing Surveys (CSUR) 34(2):171-210 (Jun. 2002).
- Compton et al., "Configuration Relocation and Defragmentation for Run-Time Reconfigurable Computing," Northwestern University, <http://citeseer.nj.nec.com/compton00configuration.html>, pp. 1-17 (2000).
- Conte et al., "Dynamic Rescheduling: A Technique for Object Code Compatibility in VLIW Architectures," Proceedings of the 28th Annual International Symposium on Microarchitecture pp. 208-218 (Nov. 29, 1995).
- Conte et al., "Instruction Fetch Mechanisms for VLIW Architectures with Compressed Encodings," Proceedings of the Annual IEEE/ACM International Symposium on Microarchitecture (MICRO) 29:201-211 (Dec. 2, 1996).
- Cray Research Inc., "Cray T3E Fortran Optimization Guide," Ver. 004-2518-002, Section 4.5 (Jan. 1999).
- Cummings et al., "FPGA in the Software Radio," IEEE Communications Magazine . 37(2):108-112 (Feb. 1999).
- Dandalis et al., "An Adaptive Cryptographic Engine for IPsec Architectures," IEEE pp. 132-141 (Jan. 2000).
- David et al., "DART: A Dynamically Reconfigurable Architecture Dealing with Future Mobile Telecommunication Constraints," Proceedings of the International Parallel and Distributed Processing Symposium pp. 156-163 (Apr. 15, 2002).
- Deepakumara et al., "FPGA Implementation of MD5 Hash Algorithm," Canadian Conference on Electrical and Computer Engineering, IEEE (2001).
- Dehon et al., "Reconfigurable Computing: What, Why and Implications for Design Automation," Design Automation Conference Proceedings pp. 610-615 (1999).
- Dipert, "Figuring Out Reconfigurable Logic," EDN 44(16):107-114 (Aug. 5, 1999).
- Dominikus, "A Hardware Implementation of MD4-Family Hash Algorithms," 9th International Conference on Electronics, Circuits and Systems IEEE (2002).
- Dorband, "aCe C Language Reference Guide," Online (Archived Mar. 2001), [http://web.archive.org/web/20000616053819/http://newton.gsfc.nasa.gov/aCe/aCe\\_dir/aCe\\_cc\\_Ref.html](http://web.archive.org/web/20000616053819/http://newton.gsfc.nasa.gov/aCe/aCe_dir/aCe_cc_Ref.html) (Mar. 2001).
- Drozdzowski, "Scheduling Multiprocessor Tasks—An Overview," Instytut Informatyki Politechnika, pp. 1-31 (Jan. 31, 1996).
- Ebeling et al., "RaPiD Reconfigurable Pipelined Datapath," Springer-Verlag, 6th International Workshop on Field-Programmable Logic and Applications pp. 126-135 (1996).

- Fawer et al., "A Multiprocessor Approach for Implementing a Time-Diversity Spread Spectrum Receiver," Proceedings of the 1990 International Zurich Seminar on Digital Communications, pp. 173-180 (Mar. 5-8, 1990).
- Fisher, "Gone Flat," *Forbes* pp. 76-79 (Oct. 2001).
- Fleischmann et al., "Prototyping Networked Embedded Systems," *Integrated Engineering*, pp. 116-119 (Feb. 1999).
- Forbes "Best of the Web—Computer Networking/Consumer Durables," *The Forbes Magnetic* 40 p. 80 (May 2001).
- Gibson, "Fresh Technologies Will Create Myriad Functions," *FT Information Technology Review*; World Wide Web at <http://technews.acm.org/articles/2000-2/0301w.html?searchterm=%22fresh+technologies%22> (Mar. 1, 2000).
- Gluth, "Integrierte Signalprozessoren," *Elektronik* 35(18):112-118 Francis Verlag GMBH, Munich, Germany (Sep. 5, 1986).
- Gokhale & Schlesinger, "A Data Parallel C and Its Platforms," Proceedings of the Fifth Symposium on the Frontiers of Massively Parallel Computation pp. 194-202 (Frontiers '95) (Feb. 1995).
- Grimm et al., "A System Architecture for Pervasive Computing," Washington University, pp. 1-6 (Sep. 2000).
- Halbwachs et al., "The Synchronous Data Flow Programming Language LUSTRE," Proceedings of the IEEE 79(9):1305-1319 (Sep. 1991).
- Hammes et al., "Cameron: High Level Language Compilation for Reconfigurable Systems," Proc. of the Intl. Conf. on Parallel Architectures and Compilation Techniques, pp. 236-244 (Oct. 1999).
- Hartenstein, "Coarse Grain Reconfigurable Architectures," Design Automation Conference, 2001. Proceedings of the ASP-DAC 2001, Asian and South Pacific Jan. 30, 2001-Feb. 2, 2001, Piscataway, NJ, US, IEEE, pp. 564-569 (Jan. 30, 2001).
- Heinz, "An Efficiently Compilable Extension of {M}odula-3 for Problem-Oriented Explicitly Parallel Programming," Proceedings of the Joint Symposium on Parallel Processing (May 1993).
- Hinden et al., "The DARPA Internet: Interconnecting Heterogeneous Computer Networks with Gateways," *IEEE Computer Magazine* pp. 38-48 (1983).
- Horton, "Beginning Java 2: JDK 1.3 Edition," Wrox Press, Chapter 8, pp. 313-316 (Feb. 2001).
- Huff et al., "Lifetime-Sensitive Modulo Scheduling," 6th Conference on Programming Language, Design and Implementation, pp. 258-267, ACM (1993).
- IBM, "Multisequencing a Single Instruction Stream Scheduling with Space-time Tradeoffs," *IBM Technical Disclosure Bulletin* 36(2):105-108 (Feb. 1, 1993).
- IEEE, "IEEE Standard Verilog Hardware Description Language," downloaded from <http://insteecs.berkeley.edu/~cs150/fa06/Labs/verilog-ieee.pdf> on Dec. 7, 2006. (Sep. 2001).
- Internet Wire, Sunbeam Joins Microsoft in University Plug and Play Forum to Establish A "Universal" Smart Appliance Technology Standard (Mar. 23, 2000).
- Ishii et al., "Parallel Variable Length Decoding with Inverse Quantization for Software MPEG-2 Decoders," Workshop on Signal Processing Systems, Design and Implementation, IEEE pp. 500-509 (Nov. 3-5, 1997).
- Isoworth, "Isoworth Beverage Dispensing Technology Worldwide Company," Brochure (May 22, 2000).
- Jain et al., "An Alternative Approach Towards the Design of Control Units," *Microelectronics and Reliability* 24(6):1009-1012 (1984).
- Jain, "Parallel Processing with the TMS320C40 Parallel Digital Signal Processor," Sonitech International Inc., pp. 13-46. Retrieved from: <http://www-s.ti.com/sc/psheets/spra031/spra031.pdf> retrieved on Apr. 14, 2004 (Feb. 1994).
- Janssen et al., "Partitioned Register File for TTAs," Proceedings of the 28th Annual International Symposium on Microarchitecture, pp. 303-312 (Nov. 1995).
- Jong-Pyng et al., "Real-Time Virtual Channel Flow Control," Proceedings of the Annual International Phoenix Conference on Computers and Communications, Conf. 13, pp. 97-103 (Apr. 12, 1994).
- Jung et al., "Efficient Hardware Controller Synthesis for Synchronous Dataflow Graph in System Level Design," Proceedings of the 13th International Symposium on System Synthesis pp. 79-84 (ISSS'00) (Sep. 2000).
- Kaufmann et al., "Digital Spread-Spectrum Multipath-Diversity Receiver for Indoor Communication," from *Pioneers to the 21st Century*; Denver, Proceedings of the Vehicular Technology Society [sic] Conference, NY, IEEE, US 2(Conf. 42):1038-1041 (May 10-13, 1992).
- Kneip et al., "An Algorithm Adapted Autonomous Controlling Concept for a Parallel Single-Chip Digital Signal Processor," *Journal of VLSI Signal Processing Systems for Signal, Image, and dVideo Technology* 16(1):31-40 (May 1, 1997).
- Lee & Messerschmitt, "Pipeline Interleaved Programmable DSP's: Synchronous Data Flow Programming," *IEEE Transactions on Acoustics, Speech, and Signal Processing ASSP-35(9):1334-1345* (Sep. 1987).
- Lee & Messerschmitt, "Synchronous Data Flow," Proceedings of the IEEE 75(9):1235-1245 (Sep. 1987).
- Lee & Parks, "Dataflow Process Networks," Proceedings of the IEEE 83(5):773-799 (May 1995).
- Liu et al., "Scheduling Algorithms for Multiprogramming in a Hard-Real-Time Environment," *Journal of the Association for Computing* 20(1):46-61 (1973).
- Llosa et al., "Lifetime-Sensitive Modulo Scheduling in a Production Environment," *IEEE Trans. on Comps.* 50(3):234-249 (Mar. 2001).
- Lu et al., "The Morphosys Dynamically Reconfigurable System-On-Chip," Proceedings of the First NASA/DOD Workshop on Evolvable Hardware, pp. 152-160 (Jul. 19, 1999).
- Mangione-Smith et al., "Seeking Solutions in Configurable Computing," *Computer* 30(12):38-43 (Dec. 1997).
- Manion, "Network CPU Adds Spice," *Electronic Engineering Times*, Issue 1126 (Aug. 14, 2000).
- Mascia & Ishii., "Neural Net Implementation on Single-Chip Digital Signal Processor," IEEE (1989).
- McGraw, "Parallel Functional Programming in Sisal: Fictions, Facts, and Future," Lawrence Livermore National Laboratory pp. 1-40 (Jul. 1993).
- Najjar et al., "High-Level Language Abstraction for Reconfigurable Computing," *Computer* 36(8) :63-69 (Aug. 2003).
- Nichols et al., "Data Management and Control-Flow Constructs in a SIMD/SPMD Parallel Language/ Compiler," Proceedings of the 3rd Symposium on the Frontiers of Massively Parallel Computation pp. 397-406 (Oct. 1990).
- OPENMP Architecture Review Board, "OpenMP C and C++ Application Program Interface," pp. 7-16 (Oct. 1998).
- Oracle Corporation, "Oracle8i JDBC Developer's Guide and Reference," Release 3, 8.1.7, pp. 10-8-10-10 (Jul. 2000).
- Pauer et al., "Algorithm Analysis and Mapping Environment for Adaptive Computing Systems: Further Results," Proc. IEEE Symposium on FPGA's for Custom Computing Machines (FCCM), Napa CA (1999).
- Pauer et al., "Algorithm Analysis and Mapping Environment for Adaptive Computing Systems," Presentation slides, Third Bi-annual Ptolemy Miniconference (1999).
- Ramamritham et al., "On Scheduling Algorithms for Real-Time Multiprocessor Systems," Algorithms and Applications, Proceedings of the International conference on Parallel Processing 3:143-152 (Aug. 8, 1989).
- Schneider, "A Parallel/Serial Trade-Off Methodology for Look-Up Table Based Decoders," Proceedings of the Design Automation Conference 34:498-503 (Jun. 9-13, 1997).
- Sidhu et al., "A Self-Reconfigurable Gate Array Architecture," 10 International Workshop on Field Programmable Logic and Applications [http://cobnitz.codeen.org:3125/citeseer.ist.psu.edu/cache/papers/cs/17524/http:zSzzSzzaarcii.usc.edu/zSzzPublicationsZSzsidsidhu\\_fp100.pdf/sidhu00selfreconfigurable.pdf](http://cobnitz.codeen.org:3125/citeseer.ist.psu.edu/cache/papers/cs/17524/http:zSzzSzzaarcii.usc.edu/zSzzPublicationsZSzsidsidhu_fp100.pdf/sidhu00selfreconfigurable.pdf) retrieved on Jun. 21, 2006 (Sep. 1, 2001).
- Smith, "Intro to ASICs: ASIC Cell Libraries," at <http://iroi.seu.edu.cn/books/asics/Book2/CH01/CH01.5.htm>, printed on Feb. 4, 2005 (Jun. 1997).
- Souza, "Computing's New Face—Reconfigurable Devices Could Rattle Supply Chain," *Electronic Buyers' News Issue 1205*, p. P.1 (Apr. 3, 2000).
- Souza, "Quicksilver Buys White Eagle," *Electronic Buyers News*, Issue 1220 (Jul. 17, 2000).

- Sriram et al., "MPEG-2 Video Decoding on the TMS320C6X DSP Architecture," Conference Record of the 32nd Asilomar Conference on Signals, Systems, and Computers, IEEE pp. 1735-1739 (Nov. 1-4, 1998).
- Steiner, "Coke Chief's Latest Daft Idea—A Cola Tap in Every House," Sunday Times (Mar. 2001).
- Sun Microsystems, "FORTRAN 3.0.1 User's Guide, Revision A," pp. 57-68 (Aug. 1994).
- Svensson, "Co's Join on Home Web Wiring Network," Associated Press Online printed on Apr. 30, 2008 (Jun. 2000).
- Tang et al., "Thread Partitioning and Scheduling Based on Cost Model," Proceedings of the Ninth Annual ACM Symposium on Parallel Algorithms and Architectures, pp. 272-281 Retrieved from: <http://doi.acm.org/10.1145/258492.2585> retrieved on Aug. 25, 2004 (1997).
- Vaya, "VITURBO: A Reconfigurable Architecture for Ubiquitous Wireless Networks," A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree Master of Science; Rice University (Aug. 2002).
- Wang et al., "Cell Search in W-CDMA," IEEE Journal on Selected Areas in Communications 18(8):1470-1482 (Aug. 2000).
- Wardell, "Help for Hurried Cooks?," Popular Science, p. 32 (May 2000).
- Whiting & Pascoe, "A History of Data-Flow Languages," IEEE Annals of the History of Computing 16(4):38-59 (1994).
- Williamson & Lee, "Synthesis of Parallel Hardware Implementations from Synchronous Dataflow Graph Specifications," Conference Record of the Thirtieth Asilomar Conference on Signals, Systems and Computers 1340-1343 (Nov. 1996).
- Wirtlin et al., "A Dynamic Instruction Set Computer," Proceedings of the IEEE Symposium on FPGA's for Custom Computing Machines, pp. 99-107 (Apr. 21, 1995).
- [www.appliancemagazine.com](http://www.appliancemagazine.com), World Wide Web at <http://web.archive.org/web/20000511085402/http://www.appliancemagazine.com/> printed on Apr. 30, 2008.
- [www.bestrom.com](http://www.bestrom.com), BreakMate™ from [www.bestrom.com](http://www.bestrom.com) printed on Apr. 29, 2008.
- [www.beverageexpress.com](http://www.beverageexpress.com), Beverage Express from [www.beverageexpress.com](http://www.beverageexpress.com) printed on Apr. 30, 2008.
- [www.Bevstar.com](http://www.Bevstar.com), Tsoworth Beverage Dispensing Technology Worldwide from [www.bevstar.com](http://www.bevstar.com) printed on Apr. 30, 2008.
- WWW.BONATOR.COM, from the World Wide Web at <http://web.archive.org/web/20000510102440/http://www.bonator.com/> printed on Apr. 30, 2008.
- [www.Ecommerce.Dewpointinc.com](http://www.Ecommerce.Dewpointinc.com), Swiss Mountain Coffees from [www.ccommerce.dewpointinc.com](http://www.ccommerce.dewpointinc.com) printed on Apr. 30, 2008.
- [www.Gateway.com](http://www.Gateway.com), World Wide Web, <http://web.archive.org/web/20000229192734/www.gateway.com/productpages/9300splash/index.shtml> Available on Mar. 3, 2000, 1 page (Mar. 3, 2000).
- [www.Icl.com](http://www.Icl.com), from the World Wide Web at <http://www.icl.com> printed on Apr. 30, 2008.
- [www.Maegherita2000.com](http://www.Maegherita2000.com); from Margherita2000.com printed Apr. 30, 2008 (Jan. 26, 2001).
- [www.Sodaclubenterprises.com](http://www.Sodaclubenterprises.com), Soda-Club Enterprises from [www.sodaclubenterprises.com](http://www.sodaclubenterprises.com) printed on Apr. 30, 2008.
- [www.Symbol.com](http://www.Symbol.com), Symbol from [www.symbol.com](http://www.symbol.com) printed on Apr. 30, 2008.
- [www.Wunderbar.com](http://www.Wunderbar.com), Wunder-Bar Dispensing Systems from [www.wunderbar.com](http://www.wunderbar.com) printed on Apr. 30, 2008.
- Xilinx, "Virtex-II Pro Platform FPGAs: Functional Description DS083-2 (v2.5)," Product Specification, pp. 13-46 (Jan. 20, 2003).
- Young, "Architecture Powers up IPSec, SSL," EETimes, Los Gatos, CA, pp. 1-4 <http://www.eetimes.com/story/OEG20011102S0065> (Nov. 2, 2001).
- Yuan et al., "A Decomposition Approach to Non-Preemptive Real-Time Scheduling," Real Time Systems 6(1):7-35 (1994).
- Zaino et al., "Algorithm Analysis and Mapping Environment for Adaptive Computing Systems," Final Technical Report, DARPA Contract F33615-97-C-1174 (Sep. 2001).
- Zhang et al., "A IV Heterogeneous Reconfigurable Processor IC for Baseband Wireless Applications," 2000 IEEE Solid.
- International Search Report for PCT/US03/34046 dated Mar. 23, 2005.
- International Search Report for PCT/US03/34049 dated Feb. 18, 2005.
- U.S. Appl. No. 10/626,833 Office Action Mailed Dec. 8, 2005.
- U.S. Appl. No. 10/626,833 Office Action Mailed Jun. 23, 2006.
- U.S. Appl. No. 11/800,577 Office Action Mailed May 28, 2008.
- U.S. Appl. No. 11/800,577 Office Action Mailed Feb. 23, 2009.



**FIG. 1**  
PRIOR ART





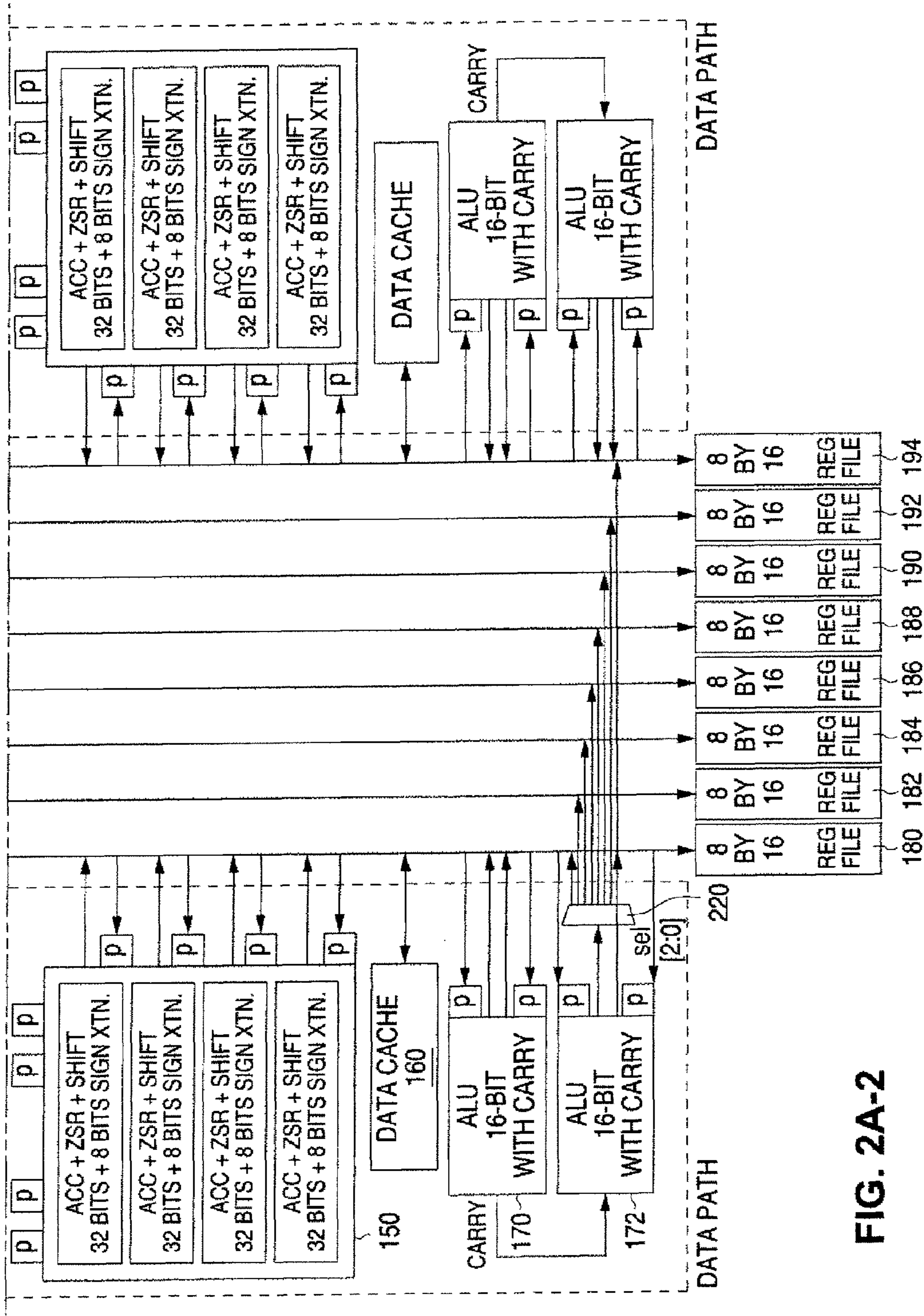


FIG. 2A-2

## ADAPTABLE DATAPATH FOR A DIGITAL PROCESSING SYSTEM

### CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 12/556,894, filed Sep. 10, 2009, which is a continuation of U.S. application Ser. No. 11/800,577, filed May 3, 2007, which is a continuation of U.S. application Ser. No. 10/626,833, filed Jul. 23, 2003, which claims the benefit of U.S. Provisional Application No. 60/422,063, filed Oct. 28, 2002, each of the aforementioned applications are incorporated by reference herein.

This application is related to the following co-pending U.S. Patent Applications that are each incorporated by reference as if set forth in full in this application: "Input Pipeline Registers For A Node In An Adaptive Computing Engine," Ser. No. 10/626,479, filed Jul. 23, 2003; "Cache For Instruction Set Architecture Using Indexes to Achieve Compression," Ser. No. 11/628,083, filed Jul. 24, 2003; "Method For Ordering Operations For Scheduling By A Modulo Scheduler For Processors With A Large Number Of Function Units And Reconfigurable Data Paths", Ser. No. 10/146,857, filed on May 15, 2002; "Uniform interface For A Functional Node In An Adaptive Computing Engine", Ser. No. 10/443,554, filed on May 21, 2003; "Hardware Task Manager For Adaptive Computing", Ser. No. 10/443,501, filed on May 21, 2003; and "Adaptive Integrated circuitry With heterogeneous And Reconfigurable Matrices Of Diverse And Adaptive Computational Units Having fixed, Application Specific Computational Element", Ser. No. 09/815,122, filed on Mar. 22, 2001.

### BACKGROUND OF THE INVENTION

This invention is related in general to digital processing architectures and more specifically to the use of an adaptable data path using register files to efficiently implement digital signal processing operations.

Digital Signal Processing (DSP) calculations require many iterations of fast multiply-accumulate and other operations. Typically, the actual operations are accomplished by "functional units" such as multipliers, adders, accumulators, shifters, etc. The functional units obtain values, or operands, from a fast main memory such as Random Access Memory (RAM). The DSP system can be included within a chip that resides in a device such as a consumer electronic device, computer, etc.

The design of a DSP chip can be targeted for specific DSP applications. For example, in a cellular telephone, a DSP chip may be optimized for Time-Division Multiple Access (TDMA) processing. A Voice-Over-Internet Protocol (VOIP) application may require vocoding operations, and so on. It is desirable for a chip manufacturer to provide a single chip design that can be adapted to different DSP applications. Such a chip is often described as an adaptable, or configurable, design.

One aspect of an adaptable design for a DSP chip includes allowing flexible and configurable routing between the different functional units, memory and other components such as registers, input/output and other resources on the chip. A traditional approach to providing flexible routing uses a data bus. Such an approach is shown in FIG. 1.

In FIG. 1, memory bus 10 interfaces with a memory (not shown) to provide values from the memory to processing components such as functional unit blocks 30, 32 and 34.

Values from memory bus 10 are selected and routed through memory bus interface 20 to data path bus 36. The functional unit blocks are able to obtain values from data path bus 36 by using traditional bus arbitration logic (e.g., address lines, bus busy, etc.). Within a block, such as functional unit block 30 of FIG. 1, there may be many different components, such as a bank of multipliers, to which the data from data path bus 36 can be transferred. In this manner, any arbitrary value from memory can be provided to any functional unit block, and to components within blocks of functional units.

Values can also be provided between functional unit blocks by using the data path bus. Another resource is register file 60 provided on data path bus 36 by register file interface 50. Register file 60 includes a bank of fast registers, or fast RAM. Register file interface 50 allows values from data path bus 36 to be exchanged with the register file. Typically, any register or memory location within register file 60 can be placed on data path bus 36 within the same amount of time (e.g., a single cycle). One way to do this is to provide an address to a location in the register file, either on the data path bus, itself, or by using a separate set of address lines. This approach is very flexible in that any value in a component of a functional unit block can be transferred to any location within the register file and vice versa.

However, a drawback with the approach of FIG. 1, is that such a design is rather expensive to create, slow and does not scale well. A bus approach requires considerable overhead in control circuitry and arbitration logic. This takes up real estate on the silicon chip and increases power consumption. The use of a large, randomly addressable register file also is quite costly and requires inclusion of tens of thousands of additional transistors. The use of such complicated logic often requires bus cycle times to be slower to accommodate all of the switching activity. Finally, such an approach does not scale well since, e.g., adding more and more functional unit blocks will require additional addressing capability that may mean more lines and logic. Additional register file space may also be required. The data path bus would also need to be routed to connect to the added components. Each functional unit block also requires the bus control and arbitration circuitry.

Thus, it is desirable to provide an interconnection scheme for digital processor applications that improves over one or more of the above, or other, shortcomings in the prior art.

### SUMMARY OF THE INVENTION

The present invention uses dedicated groups of configurable data path lines to transfer data values from a main memory to functional units. Each group of data path lines includes a register file dedicated for storage for each group of lines. Functional units can obtain values from, and store values to, main memory and can transfer values among the registers and among other functional units by using the dedicated groups of data path lines and a data address generator (DAG).

DAG circuitry interfaces each group of datapath lines to a main memory bus. Each DAG is controllable to select a value of varying bit width from the memory bus, or to select a value from another group of data path lines. In a preferred embodiment, eight groups of 16 data path lines are used. Each group includes a register file of eight 16-bit words on each group of 16 data path lines. Registers can hold a value onto their associated group of data path lines so that the value is available at a later time on the lines without the need to do a later data fetch.

In one embodiment the invention provides a data path circuit in a digital processing device, wherein the data path

circuit is coupled to a memory bus for obtaining values from a memory, the data path circuit comprising a first plurality of data lines; a first data address generator for coupling the first plurality of data lines to the memory bus so that a value from the memory transferred by the memory bus can be placed onto the first plurality of data lines; one or more functional units for performing a digital operation coupled to the plurality of data lines; and a register coupled to the first plurality of data lines, wherein the register selectively stores a value from the first plurality of data lines so that the value is selectively available on the first plurality of data lines.

Another aspect of the invention provides both general and direct data paths between array multipliers and accumulators. Banks of accumulators are coupled to the groups of configurable data path lines and are also provided with direct lines to the multipliers. An embodiment of the invention provides a digital processing system comprising a multiplier; an accumulator; a configurable data path coupled to the multiplier and the accumulator; and a direct data path coupled between the multiplier and the accumulator.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a prior art approach using a data path bus;

FIG. 2A comprising FIG. 2A-1 and FIG. 2A-2 illustrates the configurable data path arrangement of a preferred embodiment of the present invention;

#### DETAILED DESCRIPTION OF THE INVENTION

A preferred embodiment of the invention is incorporated into a node referred to as a Adaptable Node (RXN) in an adaptive computing engine (ACE) manufactured by Quicksilver, Inc., of San Jose, Calif. Details of the ACE engine and RXN node can be found in the priority and related patent applications reference above. Aspects of the invention described herein are adaptable for use with any generalized digital processing system, such as a system adapted for digital signal processing or other types of processing.

FIG. 2A comprising FIG. 2A-1 and FIG. 2A-2 illustrates the configurable data path arrangement according to a preferred embodiment of the present invention.

In FIG. 2A, digital processing system 100 is designed for fast DSP-type processing such as in discrete cosine transformation (DCT), fast fourier transformation (FFT), etc. Digital processing system 100 includes four 32-bit data path address generators (DAG) to interface between four groups of configurable data path lines 200 and a main memory bus 110. Main memory bus 110 is an arbitrated high-speed bus as is known in the art. Other types of main memory accessing can be used.

Each group of 32 lines includes two subgroups of 16 lines each. Each subgroup is connected to a register file of eight 16-bit words. For example, DAG 120 is connected to register files 180 and 182. DAG 122 is connected to register files 184 and 186. Similarly, DAGs 124 and 126 are connected to register files 188, 190 and 192, 194, respectively. Naturally, other embodiments can use any number of DAGs, groups, and subgroups register files. Although specific bit widths, numbers of lines, components, etc., and specific connectivity are described, many variations are possible and are within the

scope of the invention. Although the DAGs play a major role in the preferred embodiment, other embodiments can use other types of interfacing to the main memory bus. Although the DAGs provide a high degree of configurable routing options (as discussed below), other embodiments can vary in the degree of configurability, and in the specific configuration options and control methods. In some cases, simple registers, register files, multiplexers or other components might be used in place of the DAGs of the present invention.

The use of register files on each of the discrete subgroup lines simplifies the interconnection architecture from that of the more generalized bus and multiplexed register file shown in FIG. 1 of the prior art. This approach can also provide benefits in reduced transistor count, power consumption, improved scalability, efficient data access and other advantages. Although configuring the data path of the present invention may be more complex than with generalized approaches, in practice, a compiler is able to automatically handle the configuration transparently to a human programmer. This allows creation of faster-executing code for a variety of DSP applications by using the same hardware architecture without placing any undue burden on the programmer. If desired, a programmer can customize the data path configuration in order to further optimize processing execution.

Groups of data path lines 200 are used to transfer data from memory bus 110 to functional units within blocks 130 and 132, and also to transfer data among the functional units, themselves. The functional unit blocks are essentially the same so only block 130 is discussed in detail. Functional units include Programmable Array Multipliers (PAMs) 140, accumulators (and shift registers) 150, data cache 160 and Arithmetic/Logic Units (ALUs) 170 and 172. Naturally, the functional units used in any specific embodiment can vary in number and type from that shown in FIG. 2A.

Functional units are connected to the data path line groups via multiplexers and demultiplexers such as 210 and 220, respectively. Inputs and Outputs (I/Os) from the functional units can, optionally, use multiplexing to more than one subgroup of data path lines; or an I/O can be connected directly to one subgroup. A preferred embodiment uses pipeline registers between I/O ports and data path lines, as shown by boxes labeled "p" in FIG. 2A. Pipeline registers allow holding data at I/O ports, onto data lines, or for other purposes. The pipeline registers also allow obtaining a zero, 1, or other desired binary values and provide other advantages. Pipeline registers are described in more detail in the co-pending patent application "Input Pipeline Registers For A Node In An Adaptive Computing Engine" referenced above.

Table I, below, shows DAG operations. The configuration of the data path from cycle to cycle is set by a control word, or words obtained from the main memory bus in accordance with controller modules such as a hardware task manager, scheduler and other processes and components not shown in FIG. 2A but discussed in related patent applications. Part of the configuration information includes fields for DAG operations. A DAG operation can change from cycle to cycle and includes reading data of various widths from memory or from another DAG. DAG operations other than those shown in Table I can be used. Each DAG has one 5-bit 'dag-op' field and one 4-bit 'address' field. There is a single 'pred' field that defines non-sequencing operations.

TABLE I

Dag-op	Mnemonic	Description	Cycles
0x00	read8	Read 8-bits from memory	1
0x01	read8x	Read 8-bits from memory and sign extend to 32-bits	1
0x02	read16	Read 16-bits from memory	1
0x03	read16x	Read 16-bits from memory and sign extend to 32-bits	1
0x04	read24	Read 24-bits from memory	1
0x05	read24x	Read 24-bits from memory and sign extend to 32-bits	1
0x06	read32	Read 32-bits from memory	1
0x07	write8	Write 8-bits to memory	1
0x08	write16	Write 16-bits to memory	1
0x09	write24	Write 24-bits to memory	1
0x0A	write32	Write 32-bits to memory	1
0x0B	writeMindp	Write 32-bits (only mode supported) to MIN write queue from the data path buses	1
0x0C	writeMinM	Write 32-bits (only mode supported) to MIN write queue from a 32-bit memory read.	1 (pipelined)
0x0D	readdag16	Read a 16 bit value from one DAG register	0
0x0E	readdag32	Read a 32 bit value from two DAG registers	0
0x0F	load32dp	Load two 16-bit DAG registers or 32-bit write buffer using 32-bit data in dp2n:dp2n+1 connecting to DAGn	1
0x10	load16dpn	Load a DAG register from an even data path bus	1
0x11	load16dpn+1	Load a DAG register from an odd data path bus 1	1
0x12	modify	Modify address but do not do a memory access.	1
0x13	Dagnoop	Do nothing. All DAG operations execute every clock cycle until this operation is chosen	1
0x14	Dagcont	Continue the previous operation	1
0x15	writePA	Writes 32-bits of data from memory into 'tfrl' or 'tbrl'	1
0x16	writeMinbuf	Write 32-bits to MIN write queue from buffer	1

For dag-op: 0x00 to 0x0A, 0x0C and 0x12 the DAG operation format of Table II applies. The address field is divided into action and context as shown.

TABLE II

10	6	5	4	3	2	1	0
dag-op		action		context		pred	
5		2		2		2	

#### Action

The 'action' field describes the address modification/generation process using a set of registers (base, limit, index and delta) pointed to by the 'context' field.

TABLE 1

DAG address calculation		
action	Operation	Description
00	Supply an address and post modify	Address = Base + Index Index = Index + delta (delta is a signed value) If Index >= limit, Index = Index - limit If Index <0, Index = limit + Index
01	Supply a pre-modified address	Index = Index + delta (delta is a signed value) If Index >= limit, Index = Index - limit If Index <0, Index = limit + Index Address = Base + Index
11	Supply a bit-reversed address	Address = Base + B-Index B-Index = reverse carry add (Index + delta) (delta is a signed value) If Index >= limit, Index = Index - Limit If Index <0, Index = limit + Index

#### Context

The 'context' field is used to point at a specific DAG setting (base, limit, index and delta) on which an 'action' is performed or a DAG register is accessed (II)

TABLE 2

context encoding	
Context	Operation
00	Use setting - basen.0, limitn.0, indexn.0, deltan.0 for DAGn
01	Use setting - basen.1, limitn.1, indexn.1, deltan.1 for DAGn
10	Use setting - basen.2, limitn.2, indexn.2, deltan.2 for DAGn
11	Use setting - basen.3, limitn.3, indexn.3, deltan.3 for DAGn

For convenience, an ACTION function is defined according to the action table—ACTION (action, context) where 'action' and 'context' refer to the DAG operation fields. This function is used in the individual DAG operation descriptions.

(II) For dag-op: 0x0D to 0x11 the following DAG operation format applies:

10	6	5	4	3	2	1	0
dag-op		action		context		pred	
5		2		2		2	

The 'dag-reg' field is used to identify a specific 16-bit register (base or limit or index or delta) within a DAG 'context' as specified by the dag-reg table (below)

TABLE 3

dag-reg encoding for dag-op 0x0D, 0x10 and 0x11	
dag-reg	Register
00	base
01	limit
10	index
11	delta

For operations 0x0E and 0x0F, the dag-reg field is used to address 2 DAG registers—base and limit or index and delta or a write buffer location. In this case, the ‘dag-reg’ table is as follows:

TABLE 4

dag-reg encoding for dag-op 0x0E	
dag-reg	Register
0X	Base and limit
1X	Index and delta

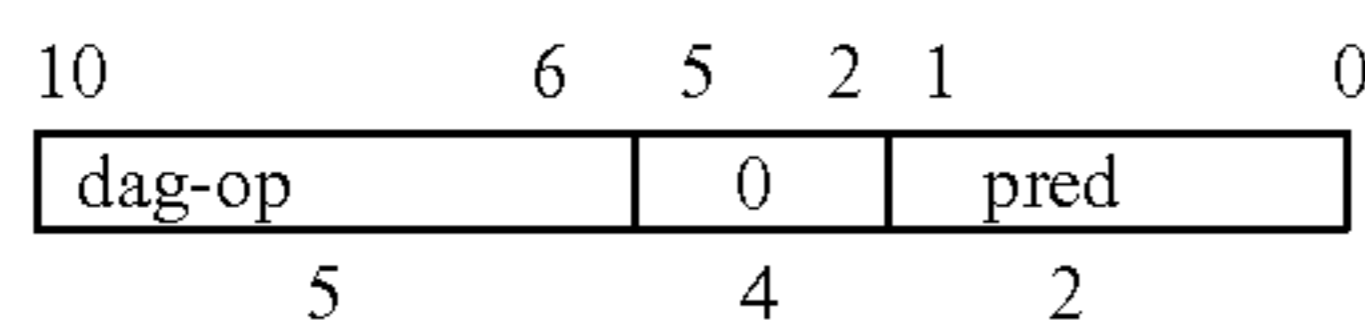
X - don't care

TABLE 5

dag-reg encoding for dag-op 0x0F	
dag-reg	Register
00	Base and limit
10	Index and delta
11	Location ‘n’ of write buffer for DAGn

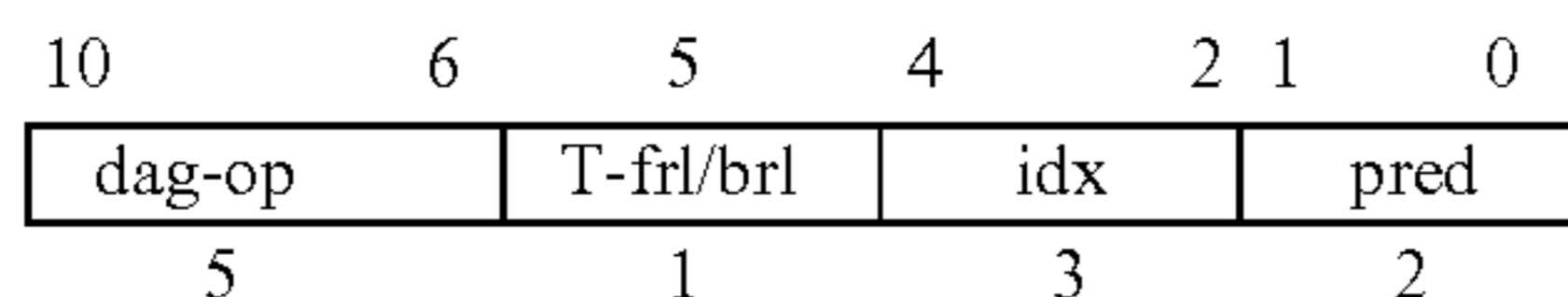
01 - undefined

(III) For dag-op: 0x0B, 0x13, 0x14, and 0x16 the following DAG operation format applies:



The address field in this case is unused, which is represented as “0” in the RXN.

(IV) For dag-op: 0x15 the following DAG operation format applies:



The ‘T-frl/brl’ field is used to choose between the translation frl and the translation brl

T-frl/brl	Operation
0	The ‘idx’ field points to T-frl
1	The ‘idx’ field points to T-brl

The T-frl and T-brl each have 5 32-bit locations. The ‘idx’ field is used to address these five locations

add	Operation
000	Location 0
001	Location 1
010	Location 2
011	Location 3
100	Location 4
101	Location 5

Pred

The universal ‘pred’ field along with the ‘s’ bit determines whether a DAG operation is executed or not executed. When a DAG operation is ‘not executed’ due to its predication, the last executed DAG operation executes again.

TABLE 6

Pred field encoding	
Pred	Description
00	Never execute
01	Always execute (execute specified operations)
10	Execute if condition is true (“s” bit is set) (execute specified operation)
11	Execute if condition is false (“s” bit is not set) (execute specified operation)
	If condition is true (“s” bit is set) (do not execute the DAG operation)
	If condition is false (“s” bit is not set) (do not execute the DAG operation)

Note:

All DAG operations execute every clock cycle until “dagnoop” operation is chosen.

Although the invention has been discussed with respect to specific embodiments thereof, these embodiments are merely illustrative, and not restrictive, of the invention. For example, although the node has been described as part of an adaptive computing machine, or environment, aspects of the filter node design, processing and functions can be used with other types of systems. In general, the number of lines and specific interconnections can vary in different embodiments. Specific components, e.g., the data address generator, can be implemented in different ways in different designs. Components may be omitted, substituted or implemented with one or more of the same or different components. For example, a data address generator can be substituted with a general register, or it can be a different component responsive to a control word. Many variations are possible.

Thus, the scope of the invention is to be determined solely by the claims.

What is claimed is:

1. A reconfigurable data path circuit coupled to a memory bus for obtaining data from a memory, the reconfigurable data path circuit comprising:

- a plurality of functional units configured to perform a digital operation;
- one or more data address generators coupled to the memory bus;
- a configurable data path configurably coupled to the one or more data address generators and the plurality of functional units, the configurable data path being configurable in response to a first configuration information by configuring or reconfiguring at least one interconnection between the one or more data address generators and the plurality of functional units;

wherein the one or more data address generators are coupled to the memory bus and the configurable data path, each of the one or more data address generators being configurable in response to a second configuration information that is different from the first configuration information to generate memory addresses from which data is to be read from or written to the memory for the data path configuration; and

wherein the second configuration information includes predication information, the generation of the memory addresses in response to the second configuration information being conditioned upon the predication information.

2. A reconfigurable data path circuit of claim 1, wherein each of the one or more data address generators is configurable as a function of both the predication information and other information in the second configuration information to determine whether to generate one of the memory addresses in response to the second configuration information.

3. The reconfigurable data path circuit of claim 2, wherein each of the one or more data address generators is configurable as a function of the predication information to operate other than generating one of the memory addresses.

4. The reconfigurable data path circuit of claim 1, wherein each of the one or more data address generators is configurable for non-sequential operation as a function of the predication information.

5. The reconfigurable data path circuit of claim 1, wherein the first and second configuration information each comprises a separate control word.

6. The reconfigurable data path circuit of claim 5, wherein each separate control word includes an operation field including the predication information.

7. The reconfigurable data path circuit of claim 6, wherein each separate control word further comprises an address field designating one of the memory addresses.

8. The reconfigurable data path circuit of claim 1, wherein the one or more data address generators are further configurable or reconfigurable in response to the second configuration information to read data of one or more widths from the memory bus consistent with and for the data path configuration.

9. The reconfigurable data path circuit of claim 1, wherein the one or more data address generators are configurable in response to the second configuration information to split data received from the memory bus onto the configurable data path.

10. The reconfigurable data path circuit of claim 9, wherein the one or more data address generators transfer data to the configurable data path for processing by the functional units in parallel.

11. The reconfigurable data path circuit of claim 1, wherein the configurable data path is reconfigurable to change from a first data path configuration having one 16 bit path to a second data path configuration having two 8 bit paths in response to the first configuration information; and each of the one or more data address generators is configurable in response to the second configuration information to generate two memory addresses for writing and reading two 8 bit words for the second data path configuration, and wherein the generation of the two memory addresses is conditioned upon the predication information.

12. The reconfigurable data path circuit of claim 1, wherein the one or more data address generators are further configurable in response to the second configuration information for transferring data to the memory bus for writing to the memory, the generation of a respective memory address for the writing of the data being conditioned upon the predication information.

13. The reconfigurable data path circuit of claim 1, wherein the plurality of functional units include a multiplier and an accumulator, the accumulator being adapted to accumulate outputs from the multipliers into a register, the reconfigurable data path circuit further comprising a direct data path coupling the multiplier and the accumulator.

14. The reconfigurable data path circuit of claim 13, wherein the plurality of functional units further includes an Arithmetic Logic Unit (ALU).

15. The reconfigurable data path circuit of claim 1, further comprising a plurality of register files each configurably

interconnected by the configurable data path to the plurality of functional units and to one of the one or more data address generators.

16. The reconfigurable data path circuit of claim 1, wherein the configurable data path further comprises a reconfigurable interconnection network configurable for configuring or reconfiguring the interconnections between the one or more data address generators and the plurality of functional units for the data path configuration.

17. The reconfigurable data path circuit of claim 16, wherein the reconfigurable interconnection network includes a plurality of groups of data lines configurably coupled to the one or more data address generators and the plurality of functional units.

18. The reconfigurable data path circuit of claim 17, wherein the reconfigurable interconnection network is configurable or reconfigurable to create portions of the reconfigurable data path having different widths, the portions being coupled between the one or more data address generators and the plurality of functional units.

19. The reconfigurable data path circuit of claim 15, wherein the configurable data path further comprises a reconfigurable interconnection network comprising a plurality of groups of data lines configurably coupled to the one or more data address generators, the functional units, and the plurality of register files in the configurable data path, wherein each register file of the plurality of register files is coupled to a group of data lines of the plurality of groups of data lines in the configurable data path in a one-to-one correspondence, the plurality of register files being adapted for storing data from the respective group of data lines to which the respective ones of the plurality of register files is coupled.

20. The reconfigurable data path circuit of claim 1, wherein the interconnections between the configurable data path and the one or more data address generators are configurable in real time.

21. The reconfigurable data path circuit of claim 1, wherein at least one of the plurality of functional units is configurable to provide at least two different functions.

22. The reconfigurable data path circuit of claim 16, wherein the plurality of functional units are configurable to provide a second plurality of configurable data paths between respective ones of the plurality of functional units and the reconfigurable interconnection network.

23. The reconfigurable data path circuit of claim 22, wherein the second plurality of configurable data paths are configurable for a plurality of data widths.

24. The reconfigurable data path circuit of claim 1, wherein each of the functional units of the plurality of functional units comprises one of a multiplier, an accumulator, a data cache, an Arithmetic Logic Unit (ALU), or a register file.

25. The reconfigurable data path circuit of claim 24, wherein the reconfigurable data path includes the multiplier, the accumulator, the data cache, the Arithmetic Logic Unit (ALU), the register file, and the reconfigurable data path includes interconnects between the functional units of the reconfigurable data path.

26. The reconfigurable data path circuit of claim 1, wherein each of the one or more data address generators is further configurable in response to the second configuration information to control memory addresses from which data is to be read from or written to the memory for the data path configuration, the control of the memory addresses in response to the second configuration information being conditioned upon the predication information.

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27. A digital processing system comprising:  
 a memory bus coupled to a memory; and  
 a reconfigurable data path circuit coupled to the memory  
 bus for obtaining data from the memory, the reconfig-  
 5 urable data path circuit comprising:  
 a plurality of functional units configurable to perform a  
 digital operation; and  
 one or more data address generators coupled to the  
 memory bus;  
 a configurable data path configurably coupled to the one or  
 10 more data address generators and the plurality of func-  
 tional units, the configurable data path being config-  
 urable in response to a first configuration information by  
 configuring or reconfiguring at least one interconnection  
 15 between the one or more data address generators and the  
 plurality of functional units;  
 wherein the one or more data address generators are  
 coupled to the memory bus and the configurable data  
 path, each of the one or more data address generators  
 being configurable in response to a second configuration  
 20 information that is different from the first configuration  
 information to generate memory addresses from which  
 data is to be read from or written to the memory for the  
 data path configuration; and  
 wherein the second configuration information includes  
 25 predication information, the generation of the memory  
 addresses in response to the second configuration infor-  
 mation being conditioned upon the predication infor-  
 mation.

28. The digital processing system of claim 27, wherein  
 30 each of the one or more data address generators is further  
 configurable in response to the second configuration infor-  
 mation to control memory addresses from which data is to be

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read from or written to the memory for the data path configu-  
 ration, the control of the memory addresses in response to the  
 second configuration information being conditioned upon the  
 predication information.

5 29. The digital processing system of claim 27, wherein  
 each of the one or more data address generators is config-  
 urable as a function of both the predication information and  
 other information in the second configuration information to  
 determine whether to generate one of the memory addresses  
 10 in response to the second configuration information.

30. The digital processing system of claim 27, wherein the  
 configurable data path further comprises a reconfigurable  
 interconnection network comprising the plurality of groups  
 of data lines and being configurable for configuring or recon-  
 15 figuring the interconnections between or among the one or  
 more data address generators and the plurality of functional  
 units for the data path configuration.

31. The digital processing system of claim 30, wherein the  
 reconfigurable interconnection network is configurable or  
 20 reconfigurable to create portions of the reconfigurable data  
 paths having different widths, the portions being coupled  
 between the one or more data address generators and the  
 plurality of functional units.

32. The digital processing system of claim 30, wherein the  
 25 plurality of functional units include a multiplier, an accumu-  
 lator, and an Arithmetic Logic Unit (ALU), the reconfigurable  
 data path circuit further comprising a direct data path cou-  
 pling the multiplier and the accumulator.

33. The digital processing system of claim 27, wherein at  
 30 least one of the plurality of functional units is configurable to  
 provide two different functions.

\* \* \* \* \*